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THE SPLIT-LOOP RESONATOR AS A SUPERCONDUCTING HEAVY ION ACCELERATING ELEMENT*

G. J. Dick† and G. D. Sprouse‡

ABSTRACT

Ion acceleration tests utilizing a superconducting split-loop resonator at accelerating potentials above 2.7 MV/m have been made on ions up to mass 29 and charge state 12. The velocity acceptance and transit time effects were measured and found to be in good agreement with theoretical estimates. Because of the very low energy content of this resonator, the rf power dissipation at low β is less than 10% of an equivalent reentrant cavity design thus relaxing requirements on the superconducting surface resistance and on the phase stabilizing system.

INTRODUCTION

A superconducting split ring resonator[1] has been operated and tested under conditions similar to those which would be required for the practical operation of a full scale accelerator. The resonator was constructed of OFHC copper covered by a 5μ layer of electroplated, chemically polished lead. It was continuously operated for extended periods of time at accelerating fields greater than 2 MV/m, and phase stabilized at 2.0 MV/m to an accuracy of .01 radian while operating at 4.2K. The resonator and its accompanying cryogenic system were than shipped by commercial carrier from California to New York where it was installed in a conventional beam line from a FN tandem Van deGraff Accelerator where it was used, without noticeable degradation of its performance, to accelerate a variety of heavy ions and to do preliminary bunching experiments. The resonator was open to the air both before initial testing, and during the transition to accelerating tests, for a total of more than 15 hours. These tests, on a resonator suitable for use in an operating accelerator, demonstrate for the first time a complete operating system appropriate to the construction of a superconducting accelerator for heavy ions.

RESONATOR CHARACTERISTICS

Figure 1 shows the resonator used for the tests described in this report. It has an optimum phase velocity given by $\beta = v/c = .058$, a value appropriate for use in the first part of a booster designed to follow an FN tandem Van de Graff accelerator. It has a resonant frequency of 238 MHz and is contructed of OFHC copper in four demountable parts. These parts are separately electroplated with lead to a thickness of approximately 8μ, chemically polished, and then assembled with indium gaskets providing electrical and thermal contact. The loop itself is hollow and is constructed of a number of parts electron beam welded together and then annealed and bent into its final shape in two separate jigs. Tolerances of a few mils can be held during this operation. The loop is mounted to the can with an indium joints which, in addition to providing electrical and thermal contact, also forms the seal between the liquid helium and the vacuum in the accelerating chamber. The currents in the two arms of the loops are equal and opposite in direction, giving no net current at the joint to the wall.

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†California Institute of Technology, Low Temperature Physics, Mail Code 63-37, Pasadena, CA 91125.
‡State University of New York at Stony Brook, Department of Physics, Stony Brook, N.Y. 11794.

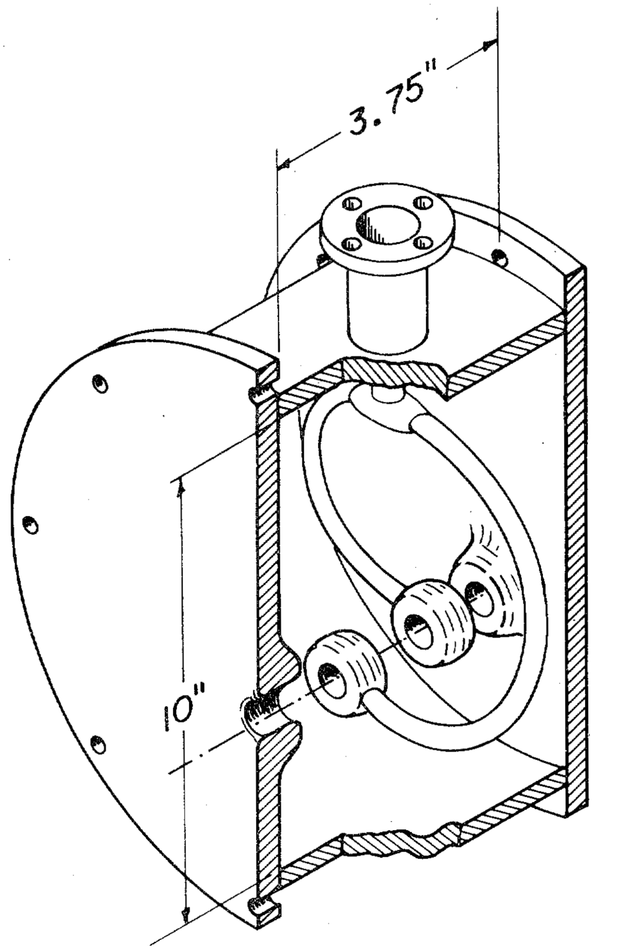

Fig. 1. The split ring structure. The dimensions shown are for the 238 MHz resonator. For other frequencies, all dimensions scale as f^{-1}.

Some of the important design features are as follows: the optimum phase velocity β is given approximately by the ratio of gap separation to total loop length. Since the potential across the center gap is twice that of the end gaps, its spacing was also chosen to be twice as long. The drift tube design requires a minimum charge to establish a given potential along the beam axis consistent with low peak electric fields.

Cooling for the resonator parts was provided in the following manner. The loop itself, where most of the rf dissipation takes place, is filled with liquid helium and is cooled by boiling. The body of the can and the end plates are cooled by conduction from a small helium "pot" directly above the mount for the loop. Pressed indium joints provide ample heat conduction for the end plates themselves.

Figure 2 shows the experimentally measured electric field profile along the beam axis for this resonator. This curve is in excellent agreement with results of drift tube calculations using an electrostatic approximation. From this data, the velocity acceptance has been derived and is shown in Fig. 3. The shape of this curve lies between those for simple two and three gap models. That is, models which contain equally spaced,

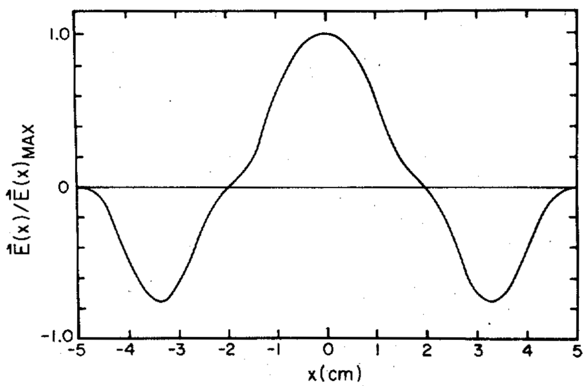

Fig. 2. Electric field along the beam axis of the split ring resonator shown in Fig. 1.

gaps, each with the same potential. The difference lies in the fact that half of the entire potential drop through this cavity occurs in the central gap. In its present configuration,it can be properly called a 2-1/2 gap cavity. If the end plates are moved farther from the ring, the velocity acceptance can be made even broader than for a simple two gap structure at some cost in overall energy gradient.

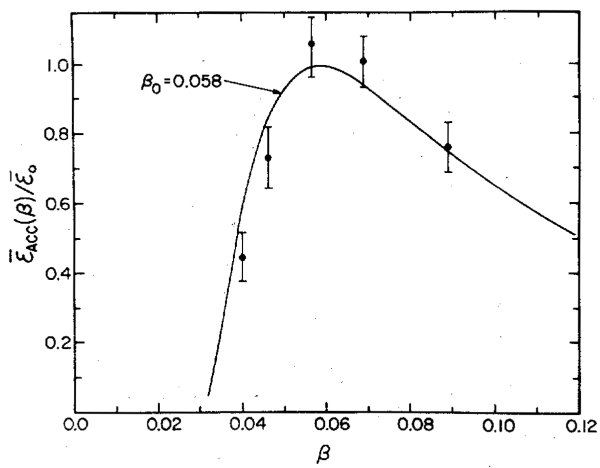

Fig. 3. Accelerating field averaged over the length of the resonator for different velocity ions normalized to the average accelerating field for the synchronous velocity.

TABLE I
Resonator-Electronic Characteristics

1. E_s = 6 MV/m (per MV/m of energy gain)
2. B_s = 100 g (")
3. Stored energy per meter at 1 MV/m
   β = 0.06 : 0.1 J (150MHz) 0.06 J (238 MHz)
   β = 0.10 : 0.2 J (") 0.1 J (")
4. Mechanical modes : 97 and 105 Hz (238 MHz)
5. Tuning power to stabilize to $\pm$ 0.01 radian (β=0.06)
   238MHz : 10 W (1MV/m) 40 W (2MV/m)
   150MHz :~50 W (") ~ 200 W (")
6. Radiation pressure frequency shift (238MHz)
   225Hz (1MV/m) 900Hz (2MV/m)

Electronic and electro-mechanical characteristics for split loop resonators are shown in Table I. Included in the table are expected values for a 150 MHz model which we believe will prove more economical than the 238 MHz resonator currently under test, and which will simplify the problems involved in bunching the incoming beam. A comparison to other types of resonators has been made previously.[1]

TABLE II
Resonator-Materials Characteristics
Cu-Pb Electroplated composite

	Small Scale	Full Scale CW	Full Scale Pulsed
1. B_c	~ 900g	300g	400g
2. E_s	50MV/m	18MV/m	25MV/m
3. $E_{acc(max)}$		3MV/m	4MV/m
4. $E_{acc(design)}$	4^oK:2.25MV/m	2^oK:2.5MV/m	
5. Q ($4-2^oK$)	$2-8 \times 10^7$		
6. Refrigeration per MV gain (at 2MV/m gradient)	4^oK:12W	2^oK:4W	

Table II shows a summary of resonator results as related to the properties of the copper-lead composite. The figures represent consistently reproducible surface properties which can be obtained in a variety of resonator configurations.

RESONATOR TESTS

After assembly and exposure to air for several hours, the resonator was operated at high fields for extended tests. As part of these tests a stabilizing procedure was demonstrated which achieved a phase error of $\pm$ 0.1 radian at 2 MV/m using a 40 watt power amplifier as the active tuning element as shown in Fig. 4.

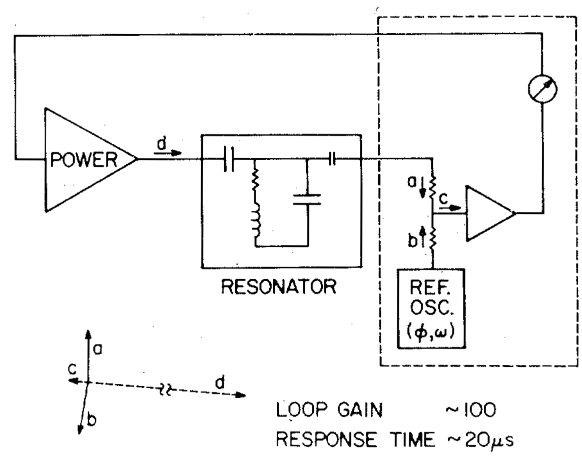

Fig. 4. Schematic diagram of circuit used to phase stabilize the 238 MHz split ring resonator.

The response time of the amplifier-stabilized resonator is just the decay time of the resonator strongly coupled to the power amplifier, reduced by the loop gain of the stabilizing system. Coupling between the amplifier and resonator was accomplished by means of a balanced, nitrogen temperature, resonant coupling line magnetically coupled to the resonator. Details of these procedures will be published elsewhere.

Continuous accelerating fields of 2.25MV/m at 4.2K and 2.75MV/m at 2.0K were maintained for many hours during these tests. The only change observable being a steady decrease in electron generated X rays omitted from the cavity as the surfaces were conditioned.[1,2]

Following these tests, the dewar was partially disassembled, shipped from California to New York, reassembled, and mounted in the beam line of the Stony Brook FN tandem Van deGraff accelerator as shown in Fig. 5. During this time, the resonator was opened several times to the air for total time of approximately 10 hours. No effect on resonator performance was observed due to this handling, nor was any subsequently observed that could be attributed to contamination due to the beam line vacuum or the beam itself.

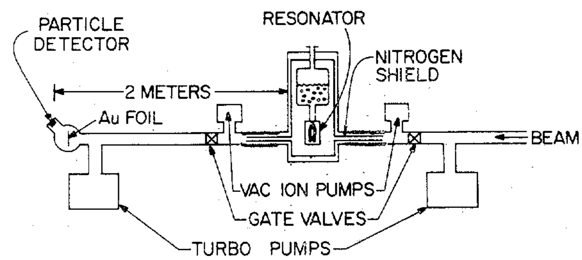

Fig. 5. Schematic diagram of the experimental arrangement.

BEAM TESTS

In the experiments, a DC beam was used. Thus some of the particles are accelerated and some decelerated according to:

$$\frac{dN}{d(\Delta E)} \propto \frac{1}{\sqrt{\Delta E_m^2 - \Delta E^2}}$$

and:

$$\Delta E_m = q \cdot d \cdot E_{acc}$$

where ΔE is the change in energy of the particle, q is the charge of the particle, and d is the length of the cavity.

The energy and time analysis of the beam were made with a 100μ x 25 mm^2 silicon surface barrier detector placed in a target chamber 2 meters from the resonator. A Au foil of thickness 0.6 mg/cm^2 was placed in the beam, and the detector was placed at 30^o to the beam direction. The energy spectrum of the elastically scattered particles was used to measure the effect of the resonator voltages on the beam.

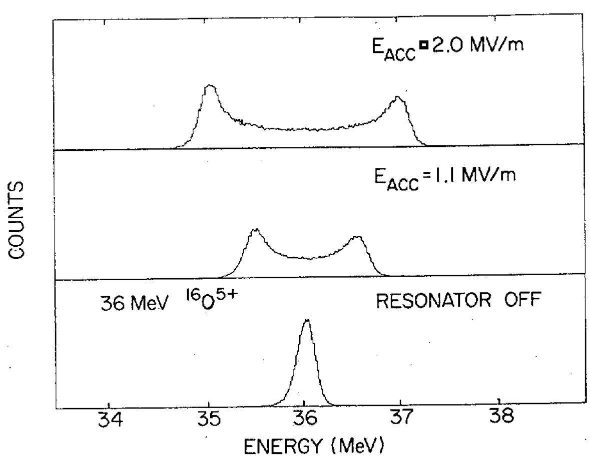

Fig. 6. Energy spectra for 35 MeV $^{16}O^{5+}$ beam.

Accelerating fields measured during beam tests were in excellent agreement (± 5%) with values calculated from dielectric bead tests and based on the measured energy content of the resonator. Typical results are shown in Fig. 6.

Figure 7 shows the time evolution of the intensity observed at the detector with the accelerating potential adjusted to bunch the beam at the detector (about .85 MV/m). The width of the spikes appears to be explained by the varying path lengths in the detector which was used.

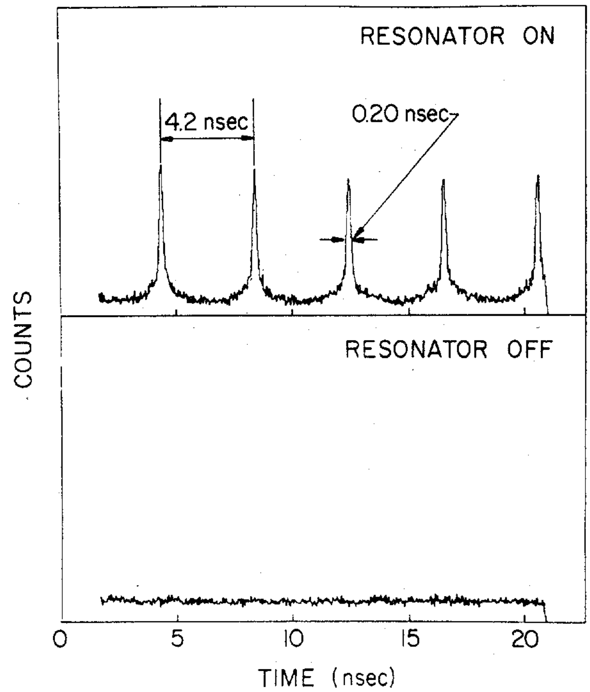

Fig. 7. Spectrum of arrival times at the detector relative to the buncher phase.

CONCLUSIONS

All the elements of a superconducting resonant structure suitable for the construction of a heavy ion booster accelerator have been successfully demonstrated under conditions appropriate to the actual building of such an accelerator. The polished superconducting lead surface has proven remarkably reproducible and durable. The structure has a very broad velocity acceptance, requiring only two types of resonators for the construction of an accelerator with a total energy gain of 10 MV/charge. A lower frequency resonator than the one which was tested will probably be desirable for reasons both of economy and bunching ease.

Based on measured results, we expect power dissipation in the accelerator to be approximately 12watts/MV at 4.2K for an accelerating field of 2 MV/m. At this level, the cost of refrigeration is a small fraction of of the overall cost of such an accelerator and there appears to be no reason to use the much more complicated refrigeration systems required for lower temperatures.

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